POSTGLACIAL VEGETATION CHANGE IN THE INTERIOR TEMPERATE RAINFOREST OF BRITISH COLUMBIA

by

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THESIS ABSTRACT

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The interior temperate rainforest of eastern British Columbia, Canada, supports dozens of species disjunct from their main coastal distribution, but the paleoecological history of this biogeographically unique area remains poorly studied. Specifically, the arrival time and migration route of the key rainforest tree species *Tsuga heterophylla* remains poorly understood. Sediment cores were obtained from two lakes occupying kame terraces on opposite sides of the upper Fraser River in east-central British Columbia. Pollen analysis indicates an early Holocene arrival time for this key species, much earlier than has previously been established and suggestive of a north-to-south migration route. Although the pollen records were broadly similar, minor differences occurred in the temporal zonation and pollen assemblages between sites. The synchronous and disparate aspects of these records shed light on the broad regional forcings of vegetation change as well as on more local factors affecting Holocene vegetation change.

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DEDICATION

I gratefully dedicate this thesis to my husband Cevin and my son Teagan, without whose support and love this (rather nontraditional) student might not have been able to suffer the slings and arrows of outrageous fortune. The whole McKern clan circled around us with their love and insights, especially my father Craig, who was willing to drive anywhere and nerd out on natural history at any time with me. My grandmother Dorothy Potter taught me to work hard and patiently, and my grandfather James Potter was wholly to blame for the genetic fascination with maps and travel that marks a true geographer.

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CHAPTER I

INTRODUCTION AND BACKGROUND

Introduction

In the Upper Fraser River valley of east-central British Columbia, many species typical of the coastal temperate rainforest occur as a disjunction and coexist with plant assemblages typical of interior montane forests. This forest association, which is marked by the late-successional tree species of *Tsuga heterophylla* (western hemlock) and *Thuja plicata* (western redcedar), extends from east-central British Columbia southward into northern Idaho (Fig 1.1). These forests, termed the Interior Cedar-Hemlock (ICH) zone, are highly valued for their impressive large trees, old-growth stands, and biodiversity (BC Integrated Land Management Bureau 2008). Compared to coastal western hemlock forests of British Columbia, there have been very few paleoecological studies within the interior cedar-hemlock zone, especially at the northern extent of its distribution. (Rosenberg, Walker, and Mathewes 2003). Paleoecological records of vegetation change in the ICH have bearing on broad questions of dispersal and climatic control of species distributions in the context of large dispersal barriers and a history of climatic changes that affected to potential range of hemlock and redcedar (e.g., Gavin 2009).

Previous paleoecological studies in the ICH showed that *Tsuga heterophylla* was not consistently present in pollen assemblages until

thousands of years after Mazama ash deposition at ca. 7.6 ka (thousands of calendar years before 1950 AD) (Rosenberg, Walker, and Mathewes 2003; Power, Whitlock, and Bartlein 2011) while along the coast it was common before 11 ka (Galloway et al. 2007). However, most paleoecological studies in the ICH focused on southeast British Columbia and Idaho. Given the unique situation of the upper Fraser River valley as an interior maritime climate fostering an ICH population that is extremely disjunct from the coast (>350 km), as well as separated by large mountain ranges from ICH forests to the south, the potential for migration lags due to limited dispersal may be more important than in other regions. Rosenberg et al. (2003) discussed potential paths by which *Tsuga heterophylla* could have migrated to the interior, but concluded too little palynological data exist to support any migration pathway. Additionally, this area lies > 600 km north of the southern limit of the Cordilleran Ice Sheet, which rapidly deglaciated at the start of the Holocene (A. S. Dyke and Prest 1987). Thus, the initial post-glacial succession may have been affected by dispersal rates of the initial colonizing species.

In the northern ICH, just south of the upper Fraser River valley, a recent study at Eleanor Lake (Fig. 1.1) shows a progression from boreal to moderated temperate climate over the Holocene, with ICH taxa only common after 4 ka (Gavin et al. 2011). Further north along the upper

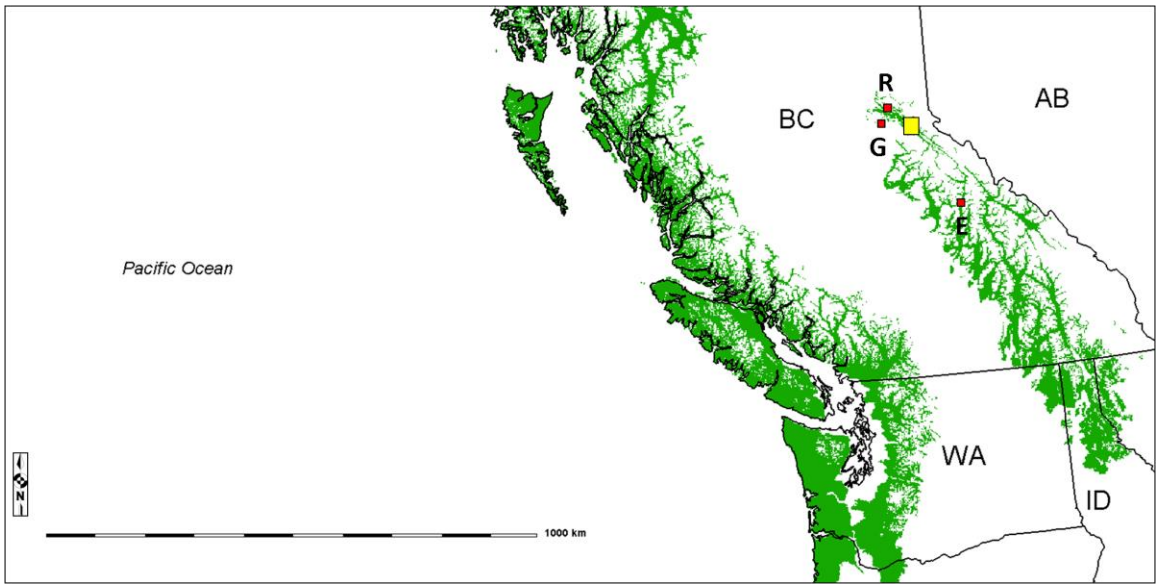

Fig. 1.1. The modern range of Tsuga heterophylla in the Pacific Northwest as determined from ecosystem zonation maps (Gavin and Hu 2006). Study area in Fig. 1.2 is represented by a yellow square. Red squares represent sites from Gavin et al. 2009 and Gavin et al. 2011: R= Redmountain Lake, G= Gerry Lake, and E= Eleanor Lake.

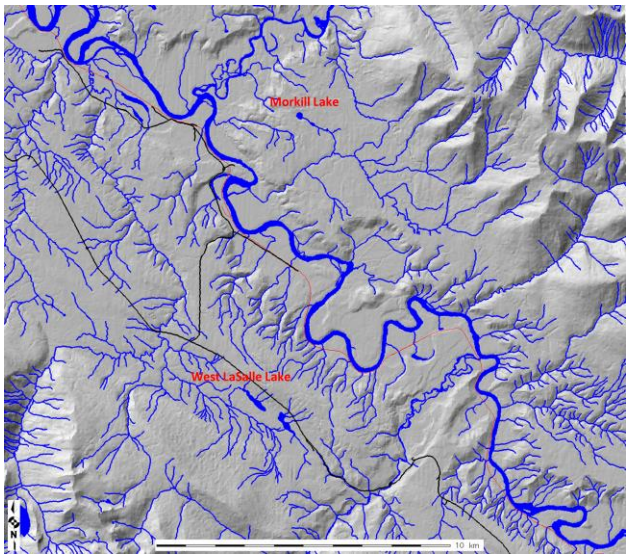

Fig. 1.2. Overview map of the study areas, located to the northeast and southwest of the main Fraser River channel.

Fraser River, pollen records from Gerry and Redmountain lakes (Fig. 1.1) suggest an arrival time of only 2 ka, but these sites are alpine, and therefore poorly suited for studying low-elevation forests (Gavin et al. 2009). Together, these sites suggest a slow northward expansion of the ICH. It remains to be seen whether the slow northward expansion of the ICH forest is upheld by paleoecological records located directly within the modern ICH and are thus well suited to study the history of this forest type.

In this study I present pollen records from two kettle lakes on opposing sides of the Fraser River (Fig. 1.2) and approximately 43 km northwest of McBride, British Columbia. The combined records should provide key data to interpret the events that shaped the cedar-hemlock rainforest in this valley from deglaciation to present.

I ask three questions:

1) What changes in forest composition and regional climate are reflected in the sediment characteristics and pollen records?
2) What was the post-glacial vegetation succession following the retreat of the Cordilleran ice sheet?
3) What insights into the migration and dispersal of ICH major taxa (e.g. *Tsuga heterophylla*) can be gained from these new pollen records?

In addition to these questions, I investigated taxonomic identification of spruce (*Picea*). The study area supports both extensive *Picea mariana*

in bogs and *Picea engelmannii x glauca* on terraces and hillslopes. New methods were developed to estimate the relative proportions of these taxa based on measured pollen grains.

Background: Overview of Paleoecological Studies in the Upper Fraser Region

Very few paleoecological studies have been published in this region of British Columbia. The purpose of this section is to acquaint readers of this thesis with previous work in the area.

Two published volumes provide background, source material, and a modern ecological perspective. The widest overview is given by the chapter in DellaSalla's book on temperate rainforests worldwide(DellaSala 2011). An in-depth study titled "British Columbia's Inland Rainforest"(Stevenson et al.) was published in 2011 and is a comprehensive modern study, but with little basis in paleoecology outside of works cited below.

Paleoecological studies in the low elevations of Fraser Valley consists solely of Sanborn's study of charcoal and fire history in the Morkill River drainage (Sanborn et al. 2006). Upper-elevation paleoecological studies were completed at Gerry and Redmountain lakes (Gavin et al. 2008), which are located 61 km north of the present study site. A recent paper examines modern plant assemblages in the valley, but with emphasis on epiphytes rather than conifers (Coxson, Björk, and

Bourassa 2013). The seminal paper on this particular forest locale has been Gavin et al.'s (2011) study of Eleanor Lake (135 km south of the study site).

The nearest research to the south is clustered in Jasper National Park. Calvin Heusser (1956) published a record from Jasper Lake, but these findings predate the availability of radiocarbon dating. One layer of tephra is identified by Heusser as Glacier Peak (6.6 ka), which indicates an arrival time of *Tsuga heterophylla* at approximately7 ka, several hundred years before ash deposition began. *Tsuga heterophylla* pollen persists between the depths of 1.9-3.4 m, which includes 30 cm of tephra. Subsequent researchers (Powers and Wilcox 1964; Zoltai 1989) found that the "Glacier Peak" tephra identified by Heusser in the 1950's in the Canadian Rockies is in many cases Mazama tephra; their study has a northeastern extent near Lake Louise, Alberta. More recent data indicates that the Bridge River tephra plume covered the northern Rockies at 2.4 ka (Mathewes and Westgate 1980). Zoltai (1989) found three distinct tephra layers in peat bogs in central Alberta and identified them as Bridge River (2.3 ka), St. Helens Y (3.4 ka) and Mazama (6.6 ka) tephras. Without analysis of the composition of Heusser's original tephra layer the most probable explanation is that what was identified as Glacier Peak tephra is actually Mazama tephra.

In addition to Heusser's work, Alwynne Beaudoin cored five lakes in the Jasper National Park area, the most well-known of which is Wilcox

Pass (Beaudoin and King 1990). These papers do not cover temperate rainforest species, focusing instead on questions of treeline and arrival times of tree species in Engelmann spruce- subalpine fir forests.

To the north, northeast, and northwest, boreal forest histories have been examined by various researchers [e.g.(Campbell and Campbell 2000), (Lynch, Hollis, and Hu 2004). These primarily support the idea that the ICH forest type has not extended northward of its current boundaries.

Southeastern BC is fertile ground for studies that have some relevance, including fire studies completed by Gavin et al. (2006) at Rockslide and Cooley Lakes, located near Nelson, BC, 550+ km south. Heinrichs studied pollen in ESSF forest near Mount Kobau (Heinrichs, Hebda, and Walker 2001). The interior rainforest extends down the western flank of the Rockies into the Idaho panhandle, where additional paleoecological studies exists (e.g., Mehringer 1986).

CHAPTER II

STUDY SITES AND METHODS

Study Sites

The upper Fraser River Valley is generally described in one of two ways depending on the classification system used. The first classification system places the study area in the Upper Fraser Trench Ecosection of the Southern Rocky Mountain Trench Ecoregion (Demarchi 2011) . This ecoregion is characterized by a mixture of moist air flow from the west intersecting with Arctic air parcels, causing heavy precipitation in the form of snow. The second classification system, the Biogeoclimatic Ecosystem Classification (BEC), places both sites in the ICHwk3 zone (the "Goat" variant of the wet-cool subzone of the Interior Cedar-Hemlock zone). This classification system uses dominant vegetation, soils, and topography to map areas of relatively uniform climate (Meidinger and Pojar 1991). The zone is marked by dominance by late-successional *Tsuga heterophylla* and *Thuja plicata*. The climate is marked by cool summers and cold winters with precipitation distributed roughly equally over the year. Mean January temperatures and precipitation at the Dome Creek climate station (located 28 km to the north-northwest of the lakes) are -9.4 °C and 84.2 mm, while July means are 14.7 °C and 76.8 mm, respectively.

The ICH zone in the Upper Fraser River occurs as a narrow band (Fig. 2.1a) between the very-wet cool subzone of the Sub-boreal Spruce

(SBSvk) zone and the wet-cool variant of the Engelmann Spruce Subalpine Fir Zone (ESSFwk1). The SBS occupies the lowest elevations that experience very cold winter temperatures from cold-air drainages. The zone is composed of *Picea engelmannii x glauca, Abies lasiocarpa,* shrubs such as *Oplopanax horribilis, Vaccinium membranaceum,* and *Rubus pedatus*, ferns such as *Gymnocarpium dryopteris,* and mosses such as *Pleurozium schreiberii. Populus balsamifera* occurs in riparian forests. The ESSF zone, in contrast, extends upslope from the upper ICH (ca. 1300 masl) to treeline (ca. 1970 masl). Species common in the ESSF include tree species of *Picea engelmannii,* and *Abies lasiocarpa* with understory species consisting of e.g. *Vaccinium membranaceum, Clintonia uniflora,* ferns such as *Gymnocarpium dryopteris,* and mosses such as *Ptilium crista-castrensis. Populus tremuloides* and *Betula papyrifera* occur on hillslopes after disturbance.

West LaSalle and Morkill Lakes are situated on different dissected kame terraces (Childs and Duncan 2008) that were formed through a complex series of deglaciation events (Fig. 2.1b).

West LaSalle Lake (53.519°N, 120.674°W) is a small kettle lake occupying a high terrace at 863 m, 216 m above the Fraser River. It has an area of 11.4 ha and a watershed size of 110 ha and a maximum depth of 7 m. West of the lake, a flat, swampy plateau extends to the base of the Cariboo Range, of which Mt. Capra (2241 m) is the nearest high peak. The lake occurs at the boundary with the SBS zone in a shallow

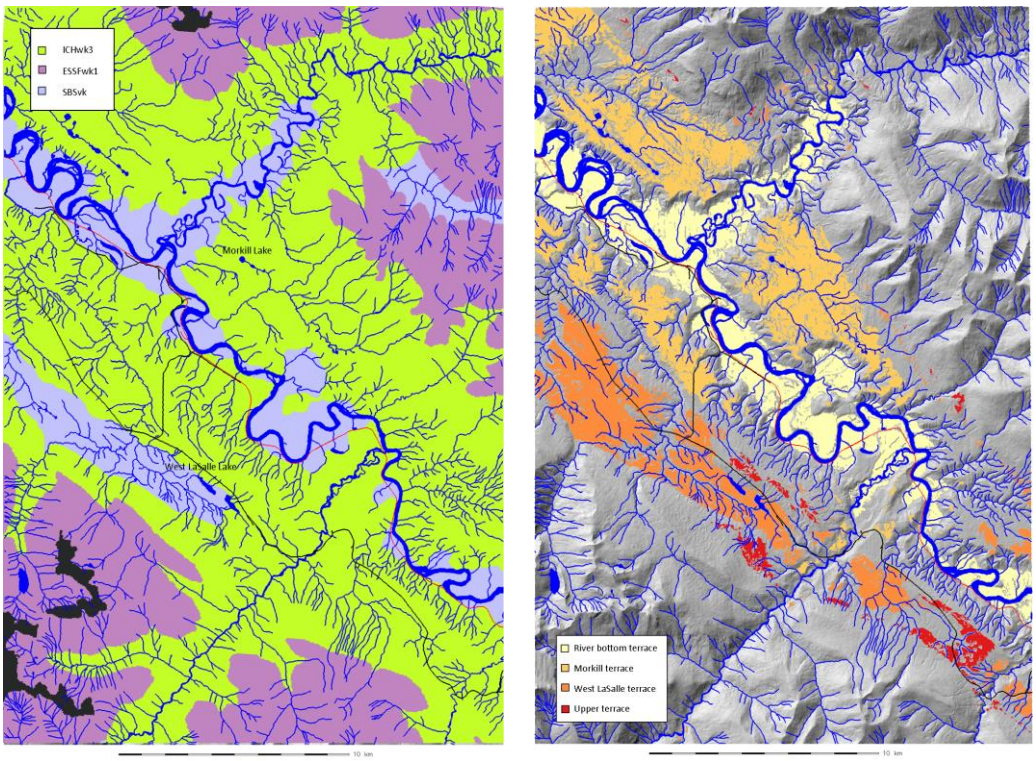

Fig. 2.1a. Biogeoclimatic zones in the study area. b. Shaded relief map of study area showing distribution of dissected kame terraces.

trough that is subject to cold-air drainages. The bedrock of the region is poorly mapped but indicates much of the area is composed of Proterozoic age sedimentary rocks of mudstone, siltstone, and shale, composed of phyllite, argillite, schist and highly sheared sedimentary mylonitic metamorphic rock units are present(Massey, N. W. D et al. 2005). A rock-core drumlin rises 79 m above the lake to the north and northeast. Core logs from recent mining prospection on this drumlin indicates it is composed of quartzite found to be extremely high in silica (>97%) and

extending hundreds of feet below ground (Childs and Duncan 2008).

Vegetation surrounding the lake is composed of *Tsuga heterophylla*, *Thuja plicata, Picea mariana* and *Abies lasiocarpa* forest with shrubs and herbs typical of the ICHwk (e.g., *Cornus canadensis, Oplopanax horribilis, Betula glandulosa, Betula pumila, Cornus stolonifera, Geum macrophyllum,* three species each of *Vaccinium* and *Salix,* and four species of *Rubus);* ferns and mosses (e.g. *Gymnocarpium dryopteris, Pleurozium schreiberii),* ten species of *Carex,* and the aquatic *Callitriche palustris* (C. Björk, *personal communication*).

Morkill Lake (53.607°N, 120.652°W) is a small kettle lake at the head of a chain of three lakes on the western side of Mt. Morkill, occurring on a glaciolacustrine terrace at 780 m elevation. The lake has an area of 4.5 ha and occupies a watershed of 19 ha. No bathymetry was recorded for the site. Bedrock near Morkill Lake is lower-Cambrian age quartzite and quartz arenite sedimentary rock(Massey, N. W. D et al. 2005). In contrast to West LaSalle Lake, the immediate surroundings are flat and support *Picea mariana* bogs. The forest is composed of *Picea engelmannii* and *Picea mariana*, with *Pinus contorta* and few *Pseudotsuga menziesii* and *Tsuga heterophylla.* Shrubs include *Betula papyriferi* and *Ledum groenlandicum*. The lake is ringed with a thick sphagnum layer. Water-edge and aquatic species noted include *Menyanthes trifoliata, Nuphar polysepalum, Potamogeton spp.* and *Drosera rotundifolia.*

Field And Laboratory Methods: West LaSalle Lake

West LaSalle Lake was cored in the summer of 2011. A modified Livingstone piston corer was used to obtain two parallel cores, 2.2 m apart. Coring continued until impenetrable silts and clays were encountered. The cores were extruded on site, wrapped in plastic wrap and stored in PVC tubes for transport. A surface core was collected using a clear plastic tube fitted with a piston, and extruded into plastic bags at 1-cm intervals while in the field.

In 2012 the core was split and the stratigraphy characterized. Magnetic susceptibility was measured at the Paleo and Environmental Magnetism Laboratory at Oregon State University using a Bartington MS-2 dual frequency susceptibility meter, with a 1-cm resolution, and photographed using a line-scan camera. A Sapphire cup meter was used to measure magnetic susceptibility of the surface core. The surface core was correlated with the Livingstone core drives using peaks in magnetic susceptibility. The parallel overlapping Livingstone drives were correlated with each other using variations in magnetic susceptibility, resulting in a continuous sediment sequence. Organic matter percentage was determined using loss on ignition at 550°C on 1-2 cm^3 subsamples (n=24). Bulk density was calculated from the same set of samples.

I used a modified Faegri & Iversen protocol (Faegri, Waterbolk, and Iversen 1964) to process sediment samples for pollen analysis measuring 1 cm^3 (n=55). A minimum of 350 terrestrial pollen grains were identified

in each sample. *Pseudotsuga/Larix* –type pollen was interpreted as *Pseudotsuga menziesii*, as the site is located 270 km north of the limit of *Larix lyalli* and 320 km north of the limit of *Larix occidentalis*. I interpreted pine pollen as *P. contorta*, as it is the only *Pinus* species known to exist locally. In the lower depths I identified a period where pollen was very rare and I was only able to identify 250 grains per sample. I included three samples from depths 437, 441, and 447 at 250 terrestrial pollen grains in the overall percentage calculations, while the terminal two samples from depths 453 and 462 were not included in overall percentage calculations because the minimum number of terrestrial pollen grains was reduced to 100. Stratigraphically constrained cluster analysis (Grimm 1987) was used to identify zones of relatively uniform pollen assemblages. Radiocarbon dates were obtained on identifiable macrofossils and charcoal at eight depths. I cleaned samples using warm 10% HCl and 10% KOH rinses prior to submitting them to the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory. I developed an age-depth model, including 95% confidence intervals, using CLAM software that was modified to calculate a monotonic cubic spline to eliminate spurious age reversals in the fitted curve (Blaauw 2010, modification Gavin 2014).

A detailed charcoal record was not developed. West LaSalle and Morkill lakes are less than ideal for the collection of a charcoal record because its margin is dominated by wetlands, which in other studies

were found to filter out the majority of charcoal that would normally be part of a lake's depositional record (Lynch, Hollis, and Hu 2004)

Field And Laboratory Methods: Morkill Lake

The Morkill Lake core was collected using a Livingstone piston corer in 2001. It was sectioned into 5-cm lengths in the field and sealed in plastic bags. AMS dating on bulk organic matter was obtained at four depths from the Accelerator Mass Spectrometry Lab at the University of Arizona. An age-depth relationship was developed following the methods used for the West LaSalle core. The core was sent to the University of Oregon for analysis in 2011, ten years after collection. In the intervening years between collection and analysis, the sediment in the bags had dried; some sections were completely dry. Due to this variable loss of water content, I was unable to calculate bulk density, or subsequently, pollen concentrations and accumulation rates. I was also not able to acquire magnetic susceptibility readings on the core due to its condition at the time of analysis. Each sample from which pollen was extracted was homogenized, as there was no way to determine depths within each 5-cm segment. The cores were initially sampled at a 500-year interval; following analysis, additional samples were processed to gain higher resolution insight into particularly dynamic times in the record. A minimum of 350 grains from each sample was identified.

Macrofossils were examined from Morkill Lake by sieving ca. 50%

of the sediment in each of x 5-cm sections at 250 µm. Loss on ignition at 550°C was performed on 1 cm^3 samples (n=55).

Picea Grain Differentiation

Selected grains of *Picea* from the West LaSalle core that were in good condition were measured along four axes for the purpose of differentiating between *P. mariana* and *P. engelmannii x glauca*, both of which are common in the upper Fraser Valley. For brevity I will refer to *P. engelmannii x glauca* as *P. glauca*. I measured a set of 352 grains at 19 depths, with an average resolution of 613 years. I measured whole grains along four axes using a calibrated eyepiece reticle, and the measurements were converted to micrometers from eyepiece units. The axes measured include grain size, corpus height, corpus breadth, and saccus width.

Several previous studies have developed methods to distinguish species of *Picea* on the basis of pollen size(Brubaker, L. B., L. J. Graumlich, and P. M. Anderson 1987; Lindbladh, O'Connor, and Jacobson 2002; Birks and Peglar 1980; Hansen and Engstrom 1985). Attempts to apply previous methods to my measurements failed due to a systematic difference in the means and variances between my measured samples and those of previous studies. Indeed, previous studies have found a wide range of mean pollen sizes for *Picea glauca* and *Picea mariana* (Tables 3.3 and 3.4). This difference may have arisen due to

regional genetic differences and the presence of the hybrid *P. glauca x engelmanni* in the study region rather than *P. glauca*.

I therefore relied on using the presence of bimodal patterns in the size distribution of the pollen grains to develop criteria to distinguish the pollen grains. Following rationale in Prentice (1981), a mixture model was fit to the entire set of measured pollen grains using the CLUSTER program (Bouman 2014). This algorithm identified the mixture of two multivariate Gaussian distributions that best described the overall dataset. It was assumed the distribution with the smaller mean values is *P. mariana*, as this is the case for all published datasets. Grains that were >3 SD from the center of each cluster were removed from the analysis (n=13). The remaining grains (n=339) were assigned a probable species based on the Mahalanobis distance to each distribution.

CHAPTER III

RESULTS

Age-Depth Relationships

A total of 464 cm of sediment was recovered from West LaSalle Lake before reaching impenetrable silt and clay. The eight radiocarbon dates fell onto an age-depth relationship revealing two peaks in sedimentation rate (Fig. 3.1; Table 3.1). From 11 to 8.5 ka the sedimentation rate decreased from 0.035 to 0.013 cm/yr, then increased to 0.081 cm/yr at 5.3 ka, decreased to 0.025 cm/yr at 3 ka and then increased again to 0.091 cm/yr at just before 1 ka. While tephras are common age markers in Holocene sediment cores at sites to the south (Gavin et al. 2011), West LaSalle is located beyond the recognized limit of Mazama tephra and no tephra was visually evident, nor was its presence suggested by magnetic susceptibility data. The lowest radiocarbon date at 452 cm calibrated to ca. 11.3 ka, suggesting a maximum age by extrapolation of ca. 11.7 ka at the core base (464 cm).

A total of 535 cm of sediment was recovered from Morkill Lake. The four radiocarbon dates indicate an initial phase of rapid sedimentation (0.20 cm/yr) before 10 ka, reaching a minimum of 0.026 cm/yr at 8 ka, then increased steadily to 0.071 cm/yr at the core top (Fig. 3.1, Table 3.2). The lowest radiocarbon date at 530-535 cm calibrated to 10.8 ka, suggesting a maximum age by extrapolation of 10.8 ka at the core base

(535 cm). It is assumed that any tephra that fell in the valley would have affected both lakes equally, and no tephra was visually observed in any of the segments of the Morkill core.

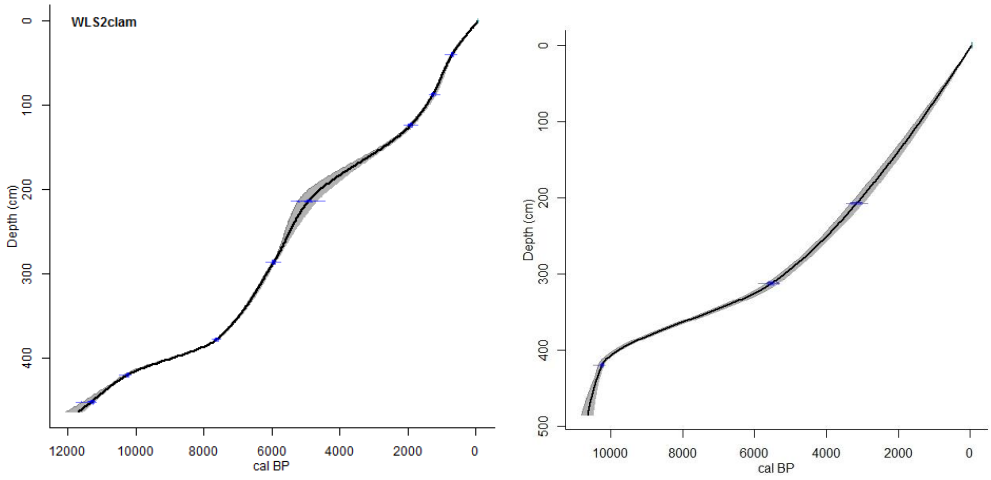

Fig. 3.1. Age–depth models for West LaSalle (left) and Morkill (right) Lakes. Fitted curves and 95% error (background) are calculated from a modified version of CLAM software.

West LaSalle Lake: Lithology and Chronology

The basal sediment (464-445 cm; >11.0 ka) consists of light gray silt and clay with very low loss-on-ignition (3%) and high magnetic susceptibility (ca. 35 x 10^{-6} cgs; Fig. 3.2). The sediment transitioned abruptly to a dark brown peaty sediment (to 435 cm; 10.8 ka) where LOI increased to 35% and magnetic susceptibility declined to negative values (ca. -8 x 10^{-6} cgs). A light brown gyttja sediment occurred until ca. 225 cm (5.0 ka), comprising fluctuating values of LOI (20-40%) and magnetic

susceptibility (-5 to -12 x 10^{-6} cgs). Above 225 cm, LOI declines and magnetic susceptibility increases gradually reaching peaks at 100 and 76 cm (1.4 and 1.0 ka, respectively). LOI at the sediment surface increases to 96%.

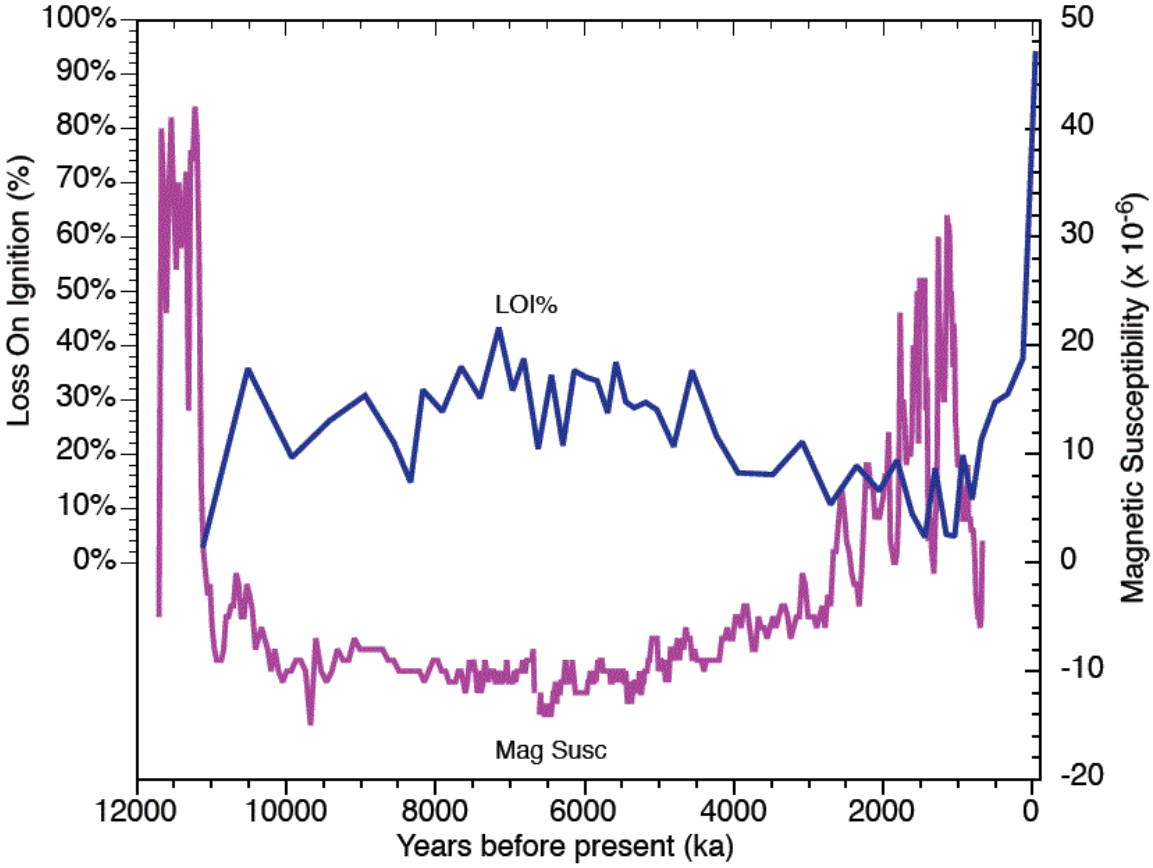

Fig. 3.2. West LaSalle Lake loss-on-ignition and magnetic susceptibility.

Table 3.1. Radiocarbon dates from West LaSalle Lake. Dates obtained from the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory. Radiocarbon ages were calibrated using the INTCAL13 calibration curve (Reimer et al.)

Lab code (CAMS#)	Depth (cm)	Dated material	^{14}C age	Calibrated age (median and 2 σ range)
164046	39	Organic detritus >250 µm: charcoal, Daphnia ephippia, insect chitin	775±30	707 (687 – 726)
164047	87	Organic detritus >250 µm: charcoal, Daphnia ephippia, insect chitin	1335±30	1270 (1246 – 1294)
164048	123.5	Charcoal >125 µm	1965±30	1925 (1891 – 1958)
159527	214	*Equisetum* sp.	4330±70	4943 (4859 – 5027)
164049	286.5	Charcoal >125 µm	5185±30	5954 (5925 – 5982)
163129	378	Conifer cone scale fragment	6780±30	7633 (7607 – 7658)
165419	420	Birch seeds (n=3), wood fragments (n=2)	9095±35	10246 (10230 – 10261)
159528	452	Conifer twig	9890±45	11300 (11252 – 11347)

Expressing the sediment organic content as a mass accumulation rate (MAR) reveals dynamic changes in the inorganic content of the

sediment (Fig. 3.3). Inorganic MAR was up to 1400 mg/cm^2/yr in the silt and clay at the core base, declined gradually from 400 to 200 mg/cm^2/yr until 8.2 ka (341 cm), increased to 800 mg/cm^2/yr at 2.2-1.7 ka (100-75 cm), then declined to near zero at the core top. In contrast, organic MAR was at a maximum just above the basal silt and clay (200 mg/cm^2/yr) then declined steadily over the length of the core to 26 mg/cm^2/yr within the last 500 years.

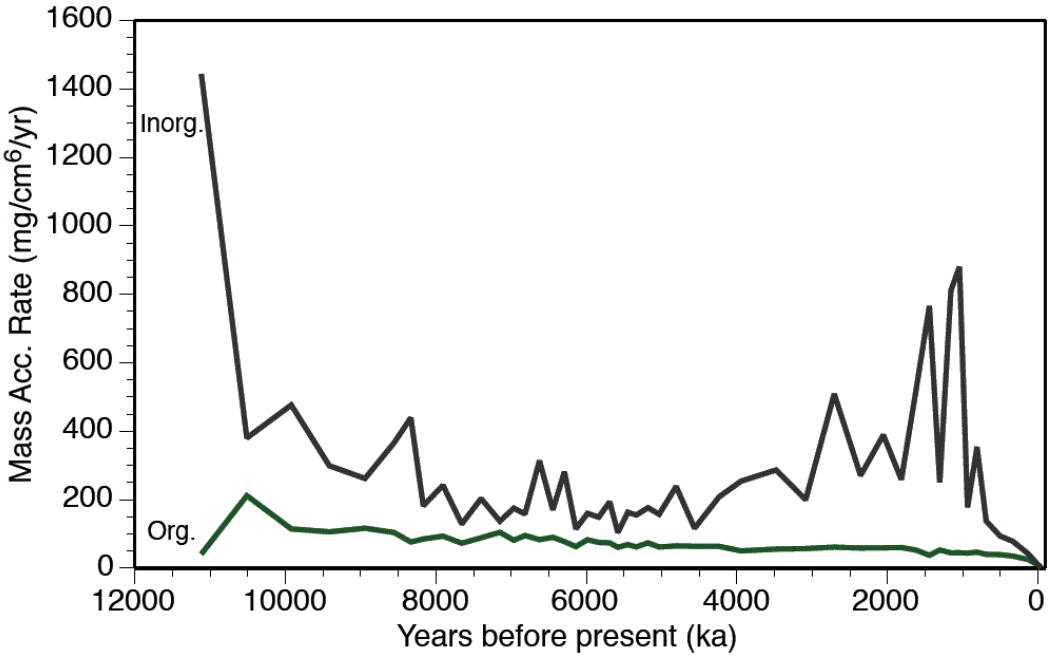

Fig. 3.3. West LaSalle inorganic and organic mass accumulation rates.

Morkill Lake: Lithology and Chronology

Lithological descriptions of the sediment core are not available as the core was sectioned in the field. This sectioning and subsequent storage caused several clay-rich samples to dry out to a hard consistency below the deepest analyzed sample dated to 10.8 ka. Loss-on-ignition

(Fig. 3.4) increases abruptly from 1% to 70% from the base (530 cm; 10.8 ka) sample until 460 cm (10.5 ka). After a brief minima of 13% at 10.3 ka, LOI values stabilize between 40 to 60%. At about 290 cm (5 ka) values rise to 50-70% and remain there to the core top.

Table 3.2 Radiocarbon dates from Morkill Lake, British Columbia. Measurements obtained from University of Arizona AMS radiocarbon facility. Radiocarbon ages were calibrated using the INTCAL13 calibration curve (Reimer et al.)

Lab code (CAMS#)	Depth (cm)	Dated material	^{14}C age	Calibrated age (median and 2 σ range)
AA46032	205-210cm	Poorly consolidated lake peat (dy)	2,979±57	3160 (3074 – 3254)
AA46033	310-315cm	Poorly consolidated lake gyttja	4,817±67	5540 (5476 – 5611)
AA46034	470-475cm	Somewhat consolidated lake gyttja	9,230±110	10430 (10297 – 10555)
AA46035	530-535cm	Fibrous lake peat with silt	9,484±53	10840 (10676 – 10998)

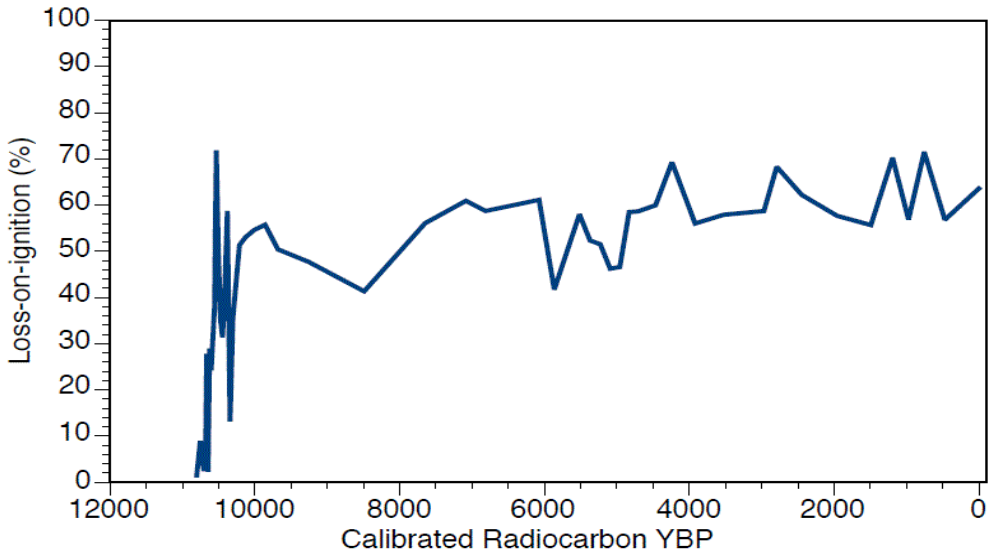

Fig. 3.4. Morkill Lake loss-on-ignition values.

West LaSalle Lake Pollen Record

Zone W1 (405-441 cm, 8.7-10.6 ka; Fig. 3.5) is marked by high percentages of *Populus* (peaking at 56%) and Poaceae (peaking at 26% in the deepest sample). This zone is lacking in conifer pollen, with low percentages of *Pinus, Cupressaceae, Pseudotsuga, Alnus*, and *Betula* summing to less than 10%. At the beginning of the zone *Artemisia* peaks at 11% as well as several aquatic and wetland taxa: *Typha* (17%), *Myriophyllum* (31%), and *Cyperaceae* (11%). Towards the end of W1, at approximately 9.64 ka, *Pinus* increases abruptly to 58%. After this zone, *Populus* is never present at levels >2%.

Zone W2 (346-405 cm, 6.9-8.7 ka) is marked by abundant *Betula* (55%) and reduced *Pinus* (which drops to 20%). Other conifers (*Picea*

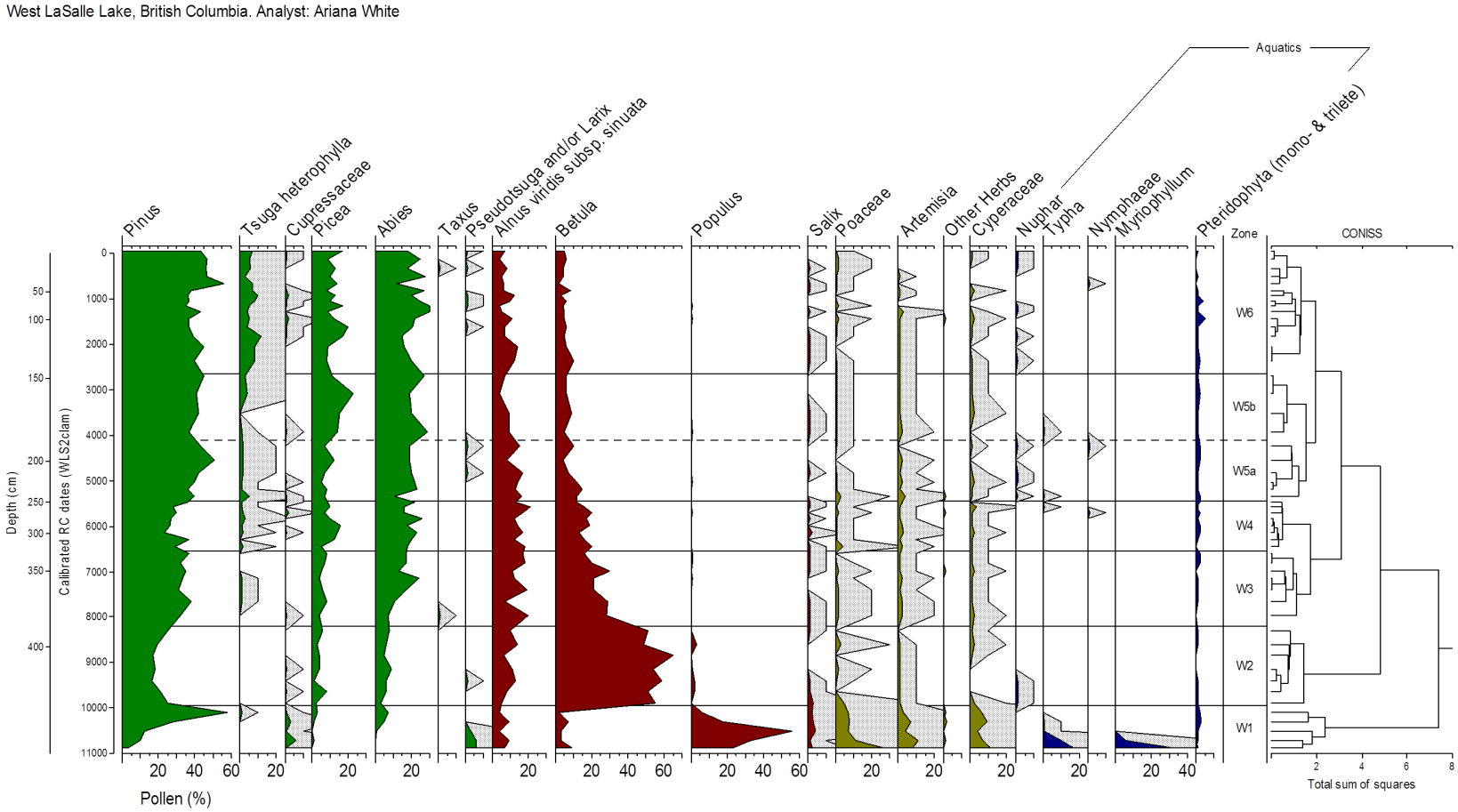

Fig. 3.5. West LaSalle Lake Pollen Diagram. Thin lines on select pollen taxa indicate 10x exaggeration of pollen percentage data. Other herbs include: *Amaranthaceae, Ambrosia-type, Ericaceae, Liliaceae, Onagraceae, Rosaceae,* and *Saxifragaceae*.

and *Abies*) are less common (<10%) and conifer pollen in total rarely exceeds 30%. *Populus* pollen declines to trace amounts at the start of the zone. *Alnus viridis* increases slightly from ca. 5 to 10%. Terrestrial herb pollen is very rare during this time period. *Nuphar* pollen occurs briefly at the start of the zone.

Zone W3 (284-345 cm, 5.9-6.9 ka) is characterized by several changes. *Betula* is the taxon with the largest change, dropping from 43 to 19%. *Abies* peaks around 7.1 ka, while *Pinus* increases from 30 to 40%. *Tsuga heterophylla* appears in continuous pollen samples from 7.9 to 7.1 ka. *Alnus* is present at 10-15%, while *Salix* is variably present, between 0-5%. *Poaceae* and Artemisia, are both present at 0-5%. Of the aquatic species, only *Nuphar* is present.

Zone W4 (234-283 cm,5.3-5.9 ka) is notable for the definitive continued presence of *Tsuga heterophylla.* Conifers are all well represented in the pollen record, including *Pinus* (30%), *Abies* (20%) and *Picea* (10%). Among hardwoods, *Alnus* averages 15% and *Betula* 17%, while *Salix* retains an average of less than 1%. *Poaceae* and *Artemisia* are present at <5%, while other herbs are only rarely present. Both *Typha* and *Nymphaea* reappear at the end of this pollen zone.

Zone W5 (124-233 cm, 1.9-5.3 ka) is divided into two parts. Zone W5a is characterized by a rise in *Pinus*, peaking at 51% at 4.56 ka, then declining slowly through subsequent zones. *Tsuga heterophylla* is

consistently present, though in very low concentrations, dropping to almost zero around the time of the shift from zone 5a to 5b. *Picea* pollen doubles from an average of 7.7% to an average of 15.8%. *Alnus* and *Betula* decrease across zone W5 from an average of 23.8% combined to an average of 13.8% combined. No *Pseudotsuga* pollen is found in this zone. Various herbs and aquatics are present at very low levels (<2%) throughout.

Zone W6 (0-123 cm, -0.060–1.9 ka) *Tsuga heterophylla* pollen is represented by percentages ranging from 3-12 (average 6.6)% during this time, and is present in every sample from 3.515 ka onward. *Cupressaceae* pollen grains are found in 9 of 15 samples in this zone. *Pinus, Abies* and *Picea* genera together comprise 75% of the total pollen count. *Alnus* is present at an average of 7.9%, while *Betula* has decreased to 5.3%. Upland herbs are restricted to *Artemisia* and *Poaceae*, with the occasional presence of other herbaceous genera. *Nuphar* is a steady presence throughout this stage.

Morkill Lake Pollen Record

Zone M1 (420-485 cm, 10.3-10.6 ka) is split into two subzones due to large fluctuations in a few taxa (Fig. 3.6). M1a exhibits high *Pinus* (to 53% in the initial sample) and moderate amounts of *Populus, Betula*, and *Alnus*, where M1b shows a decrease in *Pinus* to 23% and an increase in *Betula* to a maximum of 61% at 10.45 ka. *Alnus* and *Betula* are present

at <5% each, and *Populus* is present at 6%. *Cyperaceae* increases towards the end of this zone along with *Populus* and *Salix*. *Tsuga heterophylla* is occasionally present. The charcoal macrofossil count during this time is very high at 140 pieces per 5-cm core segment.

Zone M2 (375-420 cm, 8.8-10.2 ka) is marked by high *Betula* pollen, which has a peak of 64% at the lowest depth of the zone and averages 54% over the rest of the zone. There are continued low conifer pollen percentages: 18% *Pinus*, 4% *Picea* and 3% *Abies*. *Tsuga heterophylla* drops out and then returns in very low numbers. *Alnus* is present at 10%. *Salix* and *Populus* are present at <1%; all herbs are present at similarly low levels. Aquatic pollen types are present in low numbers. There is a peak in the numbers of *Chara spp*. oogonia at 10.11 ka (Fig. 3.7).

M3 (345-375 cm, 7.5-8.8 ka). *Betula* pollen remains the most abundant species, but declines to 42% at the end of the zone. Notable conifer species changes include a doubling of the presence of *Abies* pollen and an increase in *Pinus* pollen, which rises from 21 to 33% over the zone. *Picea* pollen increases to 8%. *Tsuga heterophylla* rises to above 2% briefly, then drops to <1% for the rest of the zone. *Alnus* pollen continues to occur at low levels. *Salix* pollen increases to a peak of 2%, then declines back to <1%. Aquatics (*Nuphar* and *Pediastrum)* are present in very low numbers. *Daphnia* ephippia start to increase.

Morkill Lake, British Columbia. Analyst: Ariana White

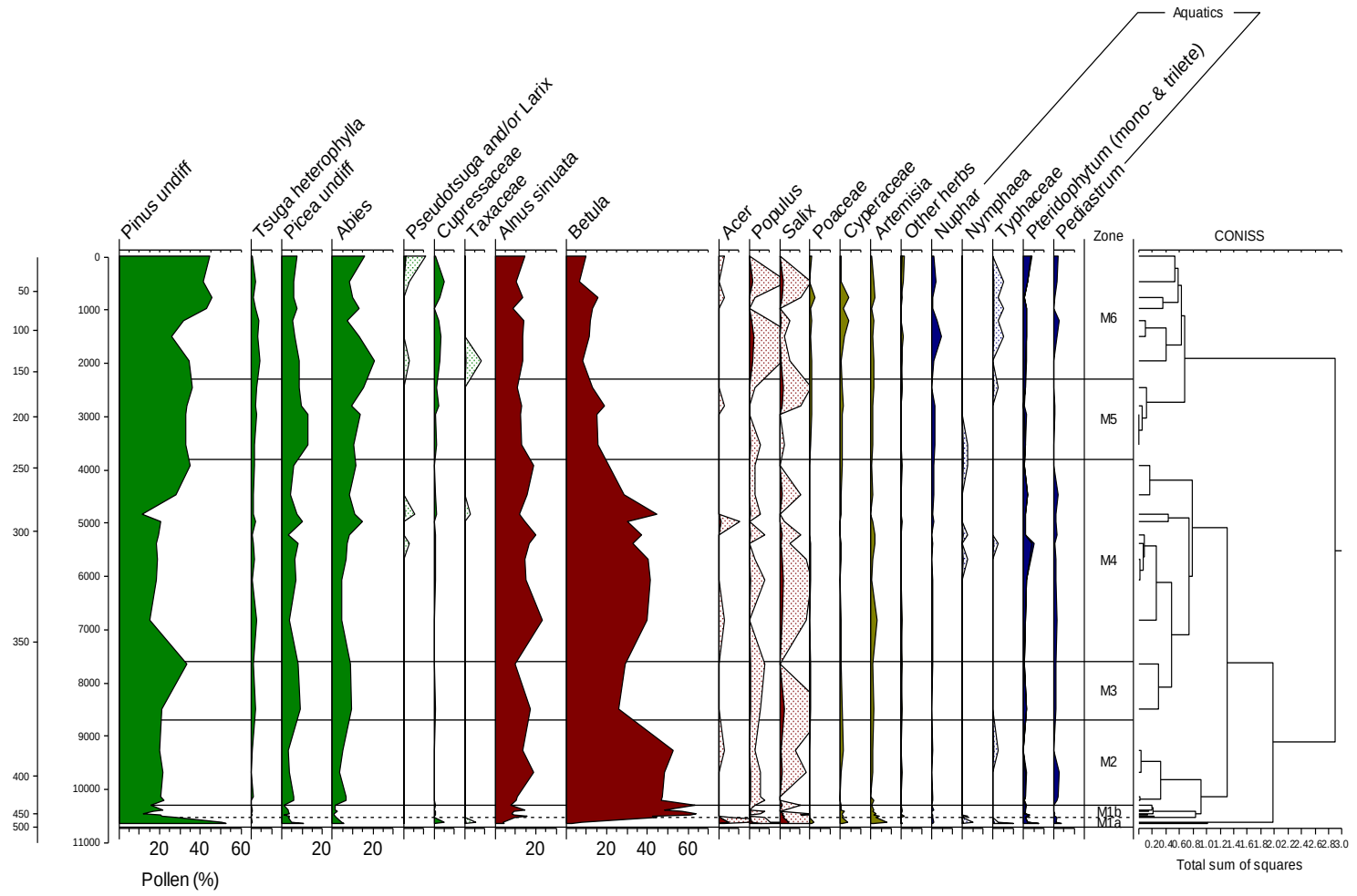

Fig. 3.6. Morkill Lake Pollen Diagram. Other herbs include *Ericaceae, Rosaceae, Onagraceae, and Liliaceae.*)

Zone M4 (230-345 cm, 3.8-7.5 ka) begins and ends with *Pinus* pollen peaks, but in the central portion of the zone there is very little change, with *Pinus* remaining at around 20% for more than 1000 years. *Betula* remains strongly present at an average of 35%, but with peaks up to 45% and a decline to 20% at the top of the zone. *Picea* remains steady at an average of 7% and *Abies* at an average of 9%. *Cristatella mucedo* statoblasts are strongly present at 4.53 ka and 5.26 ka. *Chara spp.* oogonia also peak at 5.26 ka. *Tsuga heterophylla* hovers around 1.5% during this period, with a peak of 2.4% at 4.9 ka.

In Zone M5 (165-230 cm, 2.2-3.8 ka), *Pinus* contributes 34%, while *Picea* and *Abies* contribute 11 and 12% of the total count on average, respectively. *Alnus* drops to 13% while *Betula* contributes only 16% of the total count. *Tsuga heterophylla* begins a slow rise in this zone (1.9 to 2.9%). *Salix* rises from a count of <1% to 1.6% at the end. *Cyperaceae* and *Nuphar* are present throughout but *Typha* is absent until the very end of the zone. *Daphnia spp.* ephippia peak at 3.54 ka.

Zone M6 (0-165 cm, -0.05-2.2 ka). *Tsuga heterophylla* pollen is present in constant percentages of 2-4% throughout this zone. This zone is marked by decreases in *Picea* and *Betula* and increases in *Pinus*. *Alnus* remains steady, while other hardwood taxa are present in low numbers. *Artemisia* and *Poacea* are present in small numbers throughout this time, while lake edge species (*Cyperaceae, Nuphar*, and *Typhaceae*) are

all continually present. *Pseudotsuga menziesii* is present in small numbers. Charcoal macrofossils peak at 77 pieces per 5-cm core segment at the same time that *Daphnia* ephippia show a minor peak with a count of 26.

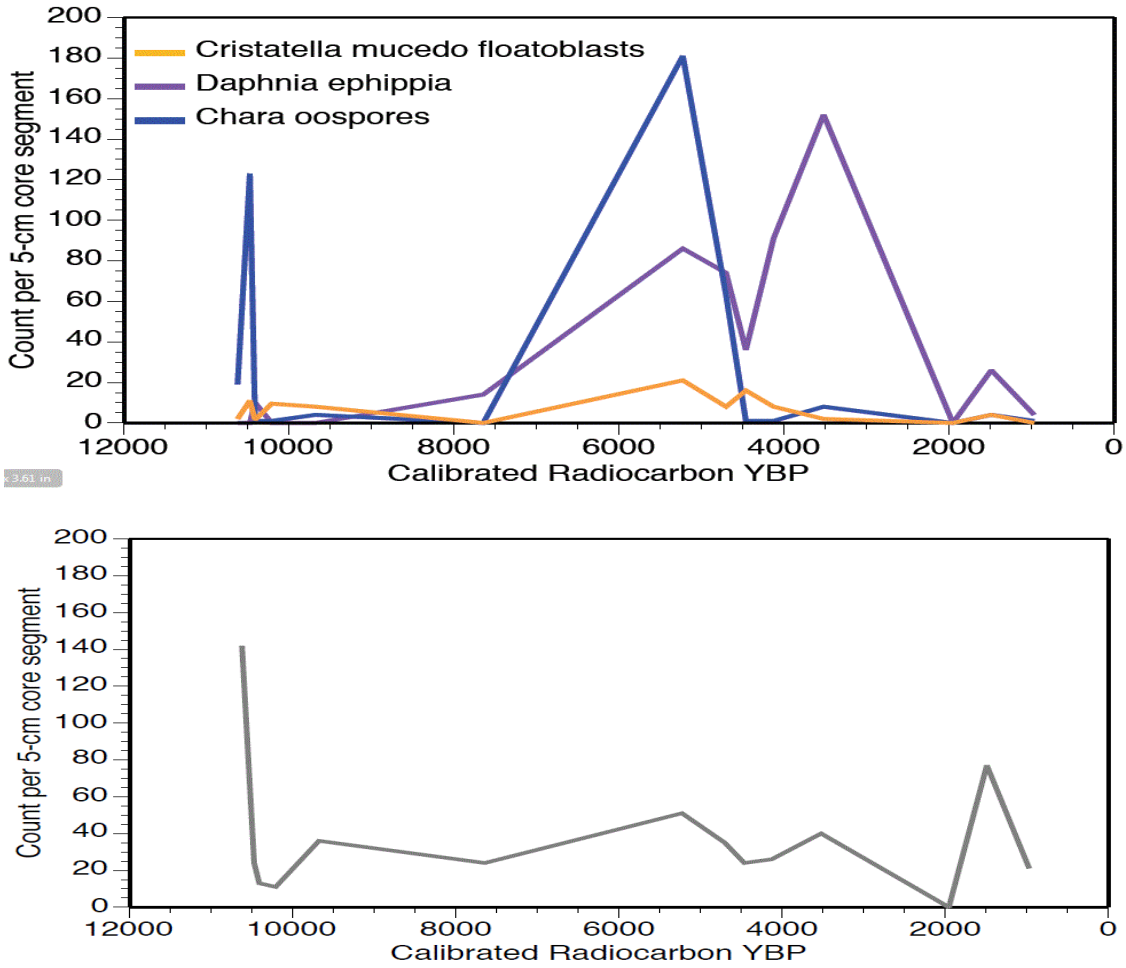

Fig. 3.7. Morkill Lake macrofossil counts. Top: Chara, Cristatella and Daphnia. Bottom: Charcoal fragments >250 µm.

Picea Differentiation and Analysis

A comparison of measurements from three studies on *Picea* mensuration and identification revealed inconsistent values among studies (Tables 3.3

and 3.4) The identification of *Picea* using my fitted Gaussian mixture model revealed that approximately 60% of the *Picea* grains were of the larger size class, assumed to be *P. engelmannii x glauca* while the remainder were of the smaller size class, assumed to be *P. mariana*. The proportion of each type did not vary very much over the past 10 ka, though one sample at ca. 7.5 ka was high in *P. mariana* (Fig. 3.8).

Table 3.3: Picea mariana measurements (in micrometers)

Reference	**Location**	**Grain size mean (1SD)**	**Corpus breadth (1SD)**	**Corpus height (1SD)**	**Saccus width (1SD)**
(Lindbladh, O'Connor, and Jacobson 2002)	Northeast North America	84.60 (9.91)	61.49 (7.43)	46.61 (6.54)	39.86 (5.56)
(Birks and Peglar 1980)	ME, WI	74.68 (7.60)	54.19 (5.25)	42.87 (3.94)	35.07 (3.67)
(Brubaker, L. B., L. J. Graumlich, and P. M. Anderson 1987)	Southeast AK	NM*	52.4 (5.6)	NM*	35.7 (4.5)
Gavin and White	Eastern BC	62.03 (6.20)	43.18 (3.28)	34.16 (3.34)	30.43 (3.46)

*Not measured

Table 3.4: Picea glauca measurements (in micrometers)

Citation:	**Location:**	**Grain size mean (1SD)**	**Corpus breadth (1SD)**	**Corpus height (1SD)**	**Saccus width (1SD)**
(Lindbladh, O'Connor, and Jacobson 2002)	NE North America	98.87 (8.01)	70.90 (6.68)	54.97 (7.30)	48.77 (6.53)
(Birks and Peglar 1980)	ME, WI	89.68 (6.31)	62.52 (4.98)	49.91 (3.79)	44.06 (3.61)
(Brubaker, L. B., L. J. Graumlich, and P. M. Anderson 1987)	Southeast AK	NM*	61.2 (6.8)	NM*	44.0 (5.4)
Gavin and White	Eastern BC	66.06(3.56)	48.31(4.73)	35.70(4.43)	34.36(4.62)

*Not measured

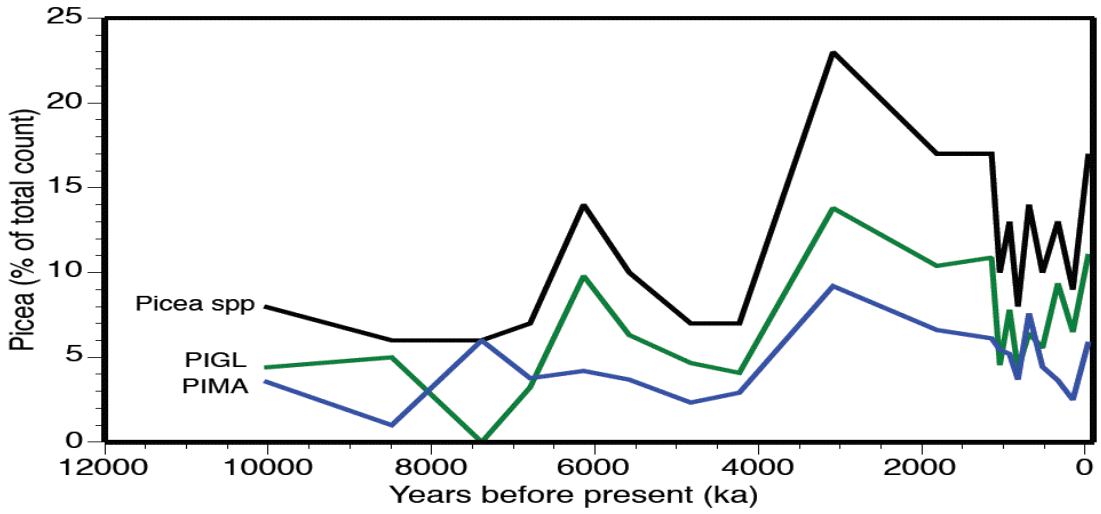

Fig. 3.8. Relative percentages of Picea species in West LaSalle Lake. Top line is percentage of all Picea species of the total pollen count.

CHAPTER IV

ENVIRONMENTAL INTERPRETATION, CONCLUSIONS, AND FUTURE RESEARCH

Environmental Interpretation

According to radiocarbon and sedimentary evidence, West LaSalle Lake formed approximately 1000 years before Morkill Lake. This is consistent with Morkill's location on a lower terrace system, which may have been under a glacier-dammed lake for some time after West LaSalle's terrace system stabilized.

The loss-on-ignition (LOI) (Fig 3.2) , shows coincident shifts in the composition of the two lakes at approximately 9.7 ka ; however, it is striking that Morkill Lake has a consistently high LOI (45-55%) while West LaSalle is much lower (20-30%). This may be due to variations in local topography. While West LaSalle is immediately in the rainshadow of the Cariboo range, Morkill is on a terrace on the eastern side of the Rockies, and is therefore well positioned to collect water as orographic precipitation falls out on the Eastern side of the valley. Additionally, cold air drainages persist on the west side of the valley near West LaSalle, and these persistently cooler temperatures may have, over the long term, had a slightly negative effect on overall productivity.

At Morkill Lake, *Betula* pollen appears in the earliest sample. It was therefore one of the first taxa to arrive at the lake site, and possibly reflects the long, cold history of this postglacial terrain, which was

actually under ice until 12 ka (A. S. Dyke and Prest 1987)

Seeds, probably *Betula* but possibly *Alnus*, were found in consistent numbers, confirming the presence of these trees within the watershed.

Species that are also prevalent throughout the record include *Pinus* and *Alnus*. Not surprisingly, *Pinus*, which represents 58% of the pollen in the initial sample, is present between percentages of 10 and 60% of all pollen throughout the core. The oldest sections of the core indicate that *Pinus* was present at high concentrations for the first 500 years after the lake was formed, but dropped dramatically soon after its formation. It remained at levels less than 40% of total pollen until approximately 5000 years BP when a sharp rise in *Pinus* pollen is observed and continues to rise gradually until the present day.

Alnus viridis is present throughout the history of the core, though until 5000 years BP its prevalence varies widely. After that time it remains at a low but stable level of about 15-20%. *Picea*, probably *Picea engelmanii x glauca* is present in low levels until its numbers increase at about 4000 years BP. *Tsuga heterophylla* is observed back to at least 8000 years in numbers that suggest local presence. Prior to that, low percentages and occasional occurrence suggest a nearby population.

Post-glacial Succession: (formation- 10.2ka)

The West LaSalle Lake sediment record provides insights into the

initial colonization of a postglacial landscape. The recession of the eastern edge of the Cordilleran ice sheet has been estimated to 11.7 ka (Ehlers and Gibbard 2004) (A. S. Dyke and Prest 1987) which is consistent with the deepest radiocarbon date at West LaSalle (11.3 ka at 452 cm) and the extrapolated age for the core base (11.7 ka at 464 cm). Evidence indicates that West LaSalle Lake was a functional lacustrine ecosystem by x ka. The earliest tree species to colonize is *Populus,* likely *Populus tremuloides*. *Artemisia* is probably a regional signal due to the warm/wet preferences of the other species present. Aquatic species suggest shallow water. The overall picture of W1 is that of a wet meadow following the tabula rasa conditions of glacial retreat.

Morkill Lake likely formed on a lower terrace at approximately 1000 years after West LaSalle was established. As noted in chapter III, I was not able to analyze the deepest 15 cm of core in this lake. The first pollen-containing samples yielded 53% *Pinus* pollen, corresponding to the high *Pinus* period that followed *Populus* at West LaSalle Lake. There is an increase in water-loving shrub species and sedges towards the end of this zone (*Populus, Salix* and *Cyperaceae).* The changes in this zone suggest early successional landscape with large areas of wetland.

Warm and Dry: (10.2 ka-8.5 ka)

Both lakes exhibit a strong initial *Betula* presence at the beginning of this time period, which is consistent with high fire activity that

eventually decreases before stabilizing. This is consistent with a regional period of frequent fire lasting from 11.0-8.8 ka (Hallett et al. 2003).

Morkill Lake's conifer signal may be drowned out by the dominance of *Betula* and *Alnus* pollen. Aquatic pollen types are present in low numbers that indicate the lake's expansion. A peak in abundance of *Chara spp.* oogonia at 10.11 ka in Morkill Lake is evidence for a pH level of >6 (cite). It is unfortunate that no fire record exists from this time.

The 9.2 ka event (Fleitmann et al. 2008) took place after this short warm period, and would have had a slight cooling effect on the valley. Following this event, a shift in the Morkill record coincides with a minor shift in the West LaSalle record, and *Tsuga heterophylla* appears in the Morkill record for the first time on a continuous basis. At West LaSalle, the shift that occurs is largely a decrease in *Abies* and *Betula* species. In other parts of Canada, this event is linked to a cooling and drying period that would indicate less fire danger and cause a decrease in disturbance-dependent species (Fleitmann et al. 2008). However, this is a change from the beginning of this period in which warmer temperatures encouraged general productivity in both lakes.

A pollen and diatom record from Eleanor Lake, BC (Gavin et al. 2011) demonstrates a similar early birch period from approximately 9.5-8.2 ka, showing that *Betula* is a regional signal rather than a signal exclusive to the Fraser River Valley. This indicates a transition to

warmer, wetter summers, although *Picea* and *Abies* appear consistently in the record for the first time during this zone.

Picea decreases through this period from 8-5% of the total count. *Picea mariana* decreases, probably due to long-term warming,drying trends which would decrease the availability of saturated, boggy soil. *Picea glauca* remains about the same.

Warm and Wet: (8.5 ka-3.8ka)

There is a noticeable early shift in the pollen record of both lakes towards warm-loving plant species such as *Betula* that seems to correlate well with the 8.5 ka event. This event involved a further significant collapse of the Laurentide ice sheet. Although the margin of the ice sheet had retreated rather far from the Rocky Mountains at this point, its cold air mass still may have had upstream effects, such as precipitation, over east-central British Columbia. There is a lag here between the climatic shift and the demonstrable change in the pollen record, reflecting a change in forest composition.

The collapse and retreat of the Laurentide ice sheet caused the jet stream to shift and led to regional warming (A. S. Dyke and Prest 1987). This warming is reflected in an increase in *Artemisia* and other pollen types, especially the disturbance- and fire-related *Betula*, which peaks early in this period and begins a long, slow decline in both lake records (dropping from 43 to 19% over the 4.3 ka that comprise this period at

West LaSalle). *Betula* continues to be a major contributor at Morkill at an average percentage for this zone of 42%, suggesting birch was more common at Morkill than at West LaSalle. In particular, the peaks in *Betula* pollen percentages at Morkill coincide roughly with charcoal deposition layers found in the Morkill valley (Sanborn et al. 2006). Specifically, a continuously high percentage of *Betula* occurs between 7 ka and 8.5 ka, during which period charcoal layers were deposited at median ages 7.07, 7.28, and 8.18 ka. Unfortunately, no older charcoal record was obtained. Hallett (2003) also notes a period of variable fire activity in southwestern BC that roughly coincides with this time period.

The macrofossil record for Morkill Lake indicates a period of warm, shallow water during 4.5-5.3 ka. *Cristatella mucedo* statoblasts and *Chara spp.* oogonia abundances indicate a lake with a temperature >10◦C and a pH of >6 and optimal shallow (<2m) depths in which to reproduce. West LaSalle shows a continuously variable assemblage of aquatic and water-edge species suggesting variation in depth. Early in this period, only *Nuphar* and *Pteridophyta* are present; they are succeeded by *Typha* and *Nymphaea,* possibly indicating lower lake levels.

Tsuga heterophylla is constantly present at West LaSalle beginning at 7.9 ka, where it remains for 800 years and then disappears from the record until 6.5 ka. Many records show a much earlier presence of *Tsuga heterophylla* in the coast rainforest following deglaciation (e.g., (Elias 2013). Hansen (1955) records the presence of an early Tsuga

heterophylla signal east of Prince George, but unfortunately his work was conducted prior to the implementation of radiocarbon dating technology, and it is not possible to determine an arrival time of *Tsuga heterophylla* from the published data. *Pinus, Abies*, and *Picea* increase and stabilize. *Poaceae* and *Artemisia* continue showing a weak regional signal, while other herbs are only rarely present. This period of stability lasts for several thousand years at both lakes.

These findings are consistent with the findings of Gavin, Hu et al (2009) at Gerry and Redmountain Lakes. At both lakes, *Tsuga heterophylla* makes an initial appearance at 6 ka. I used the guidelines set forth by Peteet in Elias (2013) for *Tsuga heterophylla* presence at the site at 2% or greater of the total pollen percentage, with values >0 but <2% indicating close proximity to the site. At Redmountain Lake, as at West LaSalle, the pattern is of an initial appearance and peak, followed by absence from the record until close to a millennium later, followed by steady presence indicating more widespread colonization. The sheltered, valley-bottom topography of Gerry and Morkill Lakes may have contributed to the establishment and persistence of *Tsuga heterophylla* in their respective locales. Redmountain Lake in particular is at a higher elevation than Morkill and West LaSalle, such that detection of low-elevation species would have required growth of large enough populations to facilitate detection, resulting in a lag when compared to a valley-bottom site such as West LaSalle lake.

Picea mariana initially rises to 6% of the total count, while *Picea glauca* is temporarily absent from the record. During this cold and wet phase, *P. mariana* may have been able to better establish in newly wet conditions on the edge of West LaSalle Lake, while *Picea glauca* may have withdrawn above the valley floor away from the damp soils at the bottom. Towards the last half of this period (7 ka-3.8 ka) all *Picea* increases to 15% of the total record, then declines to 7%. During this time, *Picea glauca* peaks and *Picea mariana* remains at about the same percentage. *Picea glauca* was therefore successful in reestablishing near the valley bottoms.

The breakdown of the stability of this mixed conifer forest is reflected in West LaSalle pollen zone 5, which straddles the transition from warm, wet forest to cool, wet rainforest. A shift in jet stream patterns (Bartlein, P. J. 1998) changed the long-term precipitation patterns to the wet-summer regime experienced through the present day.

Cool and Wet: (3.8 ka- present day)

The prevailing polar jet stream pattern that has been in place for the last 3.8 ka brings a large amount of precipitation into the interior of BC. This precipitation then falls orographically on the western side of the Rockies, supporting the ICH forest type. Increased precipitation facilitated local glacial advances during the late Holocene (Maurer et al. 2012). Therefore, the climatological basis of the interior rainforest is a

function of broad-scale features of the climate system in which moisture from the Gulf of Alaska meets the western slope of the Rocky Mountains, where convergence and orographic processes result in high precipitation.

At both lakes, *Tsuga heterophylla* pollen percentages continue to rise throughout this period against a background of well-established mixed-conifer forest. The surrounding areas are predominantly forests of the ESSF zone with pockets of ICH. *Picea mariana* and *Picea glauca* pollen types are nearly equally present, with *P. mariana* in lower abundance, probably due to its limited distribution on the margins of bodies of water. *Cyperaceae* and *Nuphar* are present at both lakes. *Artemisia* and *Poaceae* are weak regional signals.

Picea glauca and *P. mariana* peak during this time to their highest levels at 23% of the total pollen record, suggesting that they respond positively to the cool, wet climate regime. As today, *Picea mariana* likely established on saturated lake terraces while *Picea glauca* occurred on well-drained upper terraces.

Conclusions

My results establish an earlier time-of-arrival for *Tsuga heterophylla* than has previously been published, and adds support to theories of a northern migration route for this species, as it is only in records to the north and west of Morkill and West LaSalle Lakes that early presence of *Tsuga heterophylla* is recorded.

Although both pollen records provide very similar vegetation histories, some details in the records of the organic content of sediment, as well as minor differences in the pollen data, suggest local controls are also important at each site. There is no evidence for a difference in the prevailing winds that would cause any particular recurrent pattern. Westward flow would create cold air drainages at the foot of the Cariboos, enhancing the climate in which ESSF forest thrives. Alternatively, eastward flow would have a chilling or warming effect depending on the season. Current climatic data do not indicate strong prevailing wind patterns on the valley floor

The Laurentide ice sheet persisting to the east through the early Holocene may have had an effect on the climate history, even after the Fraser Valley itself is ice free. The Laurentide ice sheet does not collapse until approximately 8.2 ka, which is when a biotic shift happens in the Fraser River Valley.

These pollen records reveal a series of changing dynamics, none of which (to date) resemble any previous reference state. Certainly the Miocene forests were not very similar to the Holocene forests that are there now. It would therefore be naive to assume that any future changes will de facto represent a return to a previous state rather than a further evolution to something that lies outside our empirical knowledge, simply because it has not existed before.

The future of the rainforest is uncertain. Increasingly, precipitation

is falling as rain rather than snow, which decreases summer groundwater and creates increasingly hostile habitat for tree species that rely on it (especially *Tsuga heterophylla* and *Thuja plicata,* as well as the diverse lichen populations that form the basis for a rich food chain*).* While the annual economic value of nearby old-growth rainforest hiking trails has been as high as $180,000 CDN in 2011 and the carbon storage value, if placed in economic terms, is now higher than that for unharvested forest versus clearcut forest(Coxson 2012), the forest itself will probably shift. At no point in the history that I have examined did the plant assemblages suggest a hot and dry period. It remains to be seen how the forest will adapt to the projected rapid climate change that is probable in the centuries to come.

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